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Soil & Tillage Research 57 (2000) 159–166

Soil & Tillage Research

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Aggregate stability against water forces under different climates on agriculture land and scrubland in southern Bolivia

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Received 23 August 1999; received in revised form 1 February 2000; accepted 29 August 2000

Abstract

Little is known about the combined effect of agriculture and climate on soil aggregate stability. Few places in the world allow the study of the influences of both factors. Climatological gradients in Bolivia, where the agriculture is historically developed at different altitudes, provided opportunity to study the effects of climate and agriculture on soil aggregate stability. Aggregate stability was measured by the modified Emerson water dispersion test (MEWDT), drop impacts (CND and TDI) and ultrasonic disruption (UD) on agriculture (*Zea mays* L.) and scrubland (*Acacia caven* (Mol.) Mol., Leguminosae) land uses. Different methods and tests were applied in order to validate their ability to characterise aggregate stability. Each test had different range of energy (MEWDT < TDI < CND < UD) and thus they measured different aggregate resistance. The results showed that soil erodibility was greater under agricultural land use than under scrubland. These differences were greater at the arid site, where the scrubland soils had aggregates nine times more stable (test TDI), compared to the agricultural soil. For both lands uses, climate influenced soil aggregate stability. The higher the mean annual rainfall the greater was the soil aggregate stability. For the CND test, aggregates were between 2 and 4 times more stable on areas with 900–1000 mm yr^{-1} than on 300–400 mm yr^{-1}. Organic matter was the key factor determining soil aggregate stability on agriculture land ($r^2 = 0.80$) and scrubland ($r^2 = 0.78$) use. Agriculture was a driving force leading to the degradation of soil structure. This reflects that land use can exert a great influence on soil structure. Moreover, if climate change reduces mean annual rainfall, then aggregate stability will be reduced drastically. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Aggregate stability; Agriculture; Climate; Scrubland; Land use; Bolivia

1. Introduction

Rainfall shears off tilled aggregated soil microaggregates and macro-grains from their parents by splash impact, breaks main structural units, and causes a rapid formation of crusts resulting in depositional seals. The implication of this sequence of events is that soil aggregate breakdown is the prime regulation in the erosional system, controlling the rate of supply of material at the soil surface required to service the two responses of splash erosion and surface crusting. There is a direct relationship between an index of single aggregate stability for a soil and the erodibility of that soil (Farres, 1987). Moreover, soil aggregate stability is a synthetic parameter of the soil ecosystem due to its interactions with the flora, fauna, parent material and climate. Aggregate stability has the potential to serve as a sensitive indicator of soil

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PII: S0167-1987(00)00155-0

degradation (Imeson, 1984). Thus, aggregate stability should be controlled by the land use and climate conditions.

To study how climate determines the pedological and hydrogeomorphological processes it is possible to consider processes along climatological gradients (Lavee et al., 1991). However, few locations in the world have homogeneous agriculture management under different rainfall regimes. This was found in southern Bolivia, where three sites were selected along an altitudinal gradient of precipitation range (300–400, 600–700, 900–1000 mm yr^{-1}). This approach can be used to study the impact of climatic change on soil processes.

This paper aims to establish differences in aggregate stability along a climatological gradient under different land uses. Specific objectives were to asses different tests and differentiate between climate and land use.

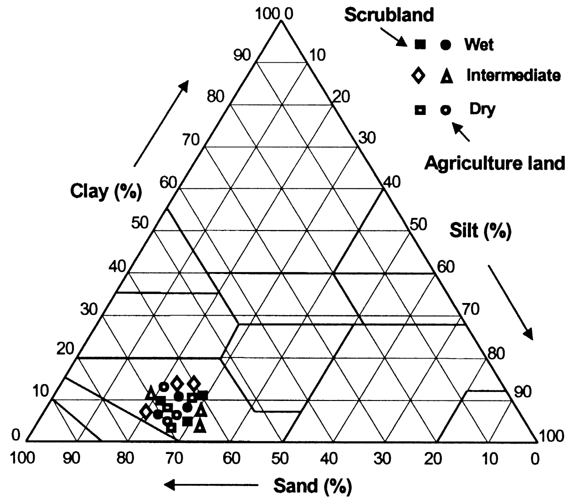

Fig. 2. Grain size of the scrubland and agriculture soils at the three different locations along the climatological gradient.

2. Methods

2.1. Study area

The study area is located in southern Bolivia within the Camacho river basin (21°S; 65°W), which ranges from 1669 to 4200 m a.s.l. (Fig. 1). Soils were classified as Regosols with low organic matter content (mean: 36 g kg^{-1}; S.D.: 19) and sandy loam soil texture (Fig. 2).

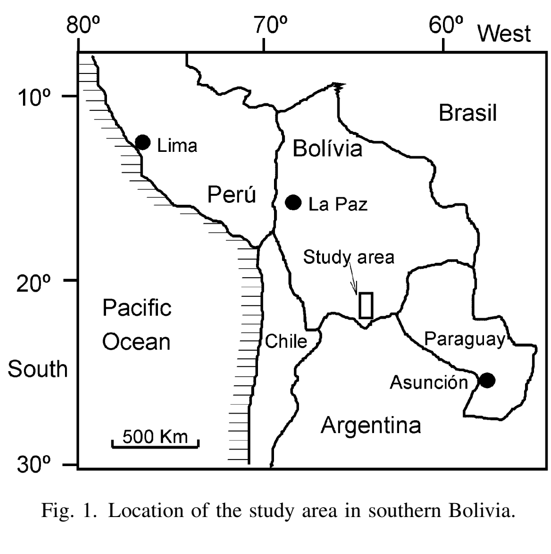

Fig. 1. Location of the study area in southern Bolivia.

The climate is heterogeneous within the basin. The lower basin is very dry (300–400 mm yr^{-1}), while the upper basin areas surpass 1400 mm yr^{-1}. For both sites, the climate is sunny and hot in summer, and very dry and quite cold in winter. Although the latitude is 21°S, it is possible to find frost in the winter month due to the south winds and the altitude (2400 m a.s.l. on average). A mild ground frost is usually present for 26 days of the year in the winter months from May to August in the lowest sites, the warmer places, and more than 100 days for the colder areas. The rainy season is from December to March, which are also the hottest months. From October to December rainfall normally falls in concentrated cloudbursts with intensities of 50 and 60 mm h^{-1}, although extreme storms of 135 mm h^{-1} have been recorded in the region.

Potential vegetation in the non-disturbed areas is dominated by the woody *Tipuana tipu* (Benth.), O. Kuntze (Leguminosae). A degradation stage of the potential vegetation is found as a typical scrubland called *churquial* (*Acacia caven* (Mol.) Mol., Leguminosae), which colonise agricultural fields after abandonment. Scrublands are used for pasture and overgrazing takes place usually during the summer. *A. caven* growths spontaneously after land abandonment and it is used as a forage, fence, and fuel materials and also as fertiliser due to its capacity to fix nitrogen. This scrubland of *A. caven* is found everywhere along the climate gradient, while the *T. tipu* is mainly found on the remote areas.

Crops are peach trees (*Prunus persica* (L.) Batsch), vineyards (*Vitis vinifera*), coime (old Inca crop, *Amarantus* spp.), potato (*Solanum tuberosum* L.), etc., but they are concentrated on different locations and not consistently along the climatological gradient. The main crop at the study area is maize (*Zea mays* L.), and it is found everywhere, thus it was selected for use in this study.

2.2. Soil sampling

Sampling on scrubland and agriculture land use took place during August 1994, after cropping and under very dry conditions. Plots were selected on the fluvial terraces in order to have similar parent material along the gradient. Samples were selected from the top surface layer (0–2 cm) which is the key layer for water erosion processes. Three different samples were selected at each of the three study sites on the scrubland and agriculture land use (3 samples × 3 sites× 2 land uses). The study sites were the following:

1. *Alisos*: wet site (900–1000 mm yr^{-1}).
2. *Juntas*: intermediate site (600–700 mm yr^{-1}).
3. *Colón Norte-Concepción*: arid site (300–400 mm yr^{-1}).

Aggregates of 4–4.8 mm in diameter were selected by sieving, and four different tests were applied to each sample: modified Emerson water dispersion test (MEWDT) (Emerson, 1967), drop-test (CND and TDI) (Imeson and Vis, 1984) and ultrasonic disruption (UD) test. In total 72 soil samples were analysed (2 land uses × 3 sites × 3 plots × 4 tests) and 3160 aggregates were used to determine the aggregate stability of the studied soils. Soil organic matter was measured by the Walkley and Black (1934) method at each of the 18 study sites.

2.3. Laboratory test

Aggregate stability tests were performed for initially air-dried aggregates and then for wetted aggregates (moistening the 4–4.8 mm fraction at 1 kPa for 24 h with a suction plate). The mean and standard deviation of the values measured for each test shown were used to differentiate between sites.

2.3.1. MEWDT

MEWDT was applied to each sample for 10 aggregates (4–4.8 mm). The procedure was to immerse the aggregates in 40 ml of distilled water at time intervals of 5, 120 min (2 h) and 1440 min (1 day) and determine the degree (on a scale of 0–4) of aggregate dispersion:

0. No dispersion. Aggregate completely entire.
1. Dispersion of some particles. Milkiness close to the aggregate.
2. Aggregate partly dispersed or divided into different smaller aggregates.
3. Considerable dispersion. Most of the aggregates were dispersed and the milkiness is very large.
4. Total dispersion. The aggregate does not exist.

2.3.2. Water-drop test

Water-drop test, a burette nozzle with silicon tubing was used, together with a constant head supply system. The drops produced with distilled water had a weight of 0.1 g at 1 s intervals. They were allowed to fall through a polythene pipe (15 cm diameter) from 1 m height onto aggregates (4–4.8 mm) placed on a 2.8 mm gauge metal sieve. Twenty aggregates were selected for each sample. The water-drop test is an established technique and there are many possible procedures. The Imeson and Vis (1984) procedure was followed, and two tests were applied here:

- *Counting the number of drop impacts* (*CND*). CND required to disrupt the aggregate sufficiently for it to pass through the 2.8 mm sieve. The number of aggregates surviving the drop impacts is an index of the aggregate stability.
- *Ten drop impacts* (*TDIs*). The weight of aggregates >2.8 mm were measured after applying TDIs.

Similar water-drop tests have been used previously by different authors (Farres, 1987; Imeson and Vis, 1984). Mean number of drop impacts, the standard deviation and the number of drops necessary to reach the breakdown of 20 aggregates were calculated.

2.3.3. UD

Ten aggregates (4–4.8 mm) moistened at pF_1 were immersed in 40 ml of distilled water, and then subjected to the ultrasound of Sanfier 1312 cell destructor (Branson Sonic Power, Danbury, CT) for 5 or 10 s with the probe tip placed 10 mm under the water surface. The energy applied varied between 30 and 115 W. After the treatment the surviving aggregates (>2.8 mm) and the aggregate fragments (<2.8 mm) were weighed (Imeson and Vis, 1984), and used as indexes of aggregate stability.

3. Results and discussion

3.1. MEWDT

Soil aggregate stability was much lower under agriculture than under scrubland use (Table 1). Under scrubland conditions, after 5 min immersion the dispersion indexes ranged from 0 on the wet site to 1–3.4 on the arid site. After 1 day of immersion the dispersion index ranged from 0.1–0.2 on the wet site to 2.1–3.9 on the arid site. Under agricultural use and after 5 min immersion the dispersion index ranged from 0.2 to 0.3 on the wet site and from 3.4 to 3.9 on the arid site. After 1 day of immersion the dispersion index was 0.8–1.1 on the wet site and 4 on the arid site. On the wettest site, aggregates had a lower dispersion index than on the arid sites for both the agriculture and the scrubland use.

3.2. Water-drop impact tests

The TDI index always showed greater stability of aggregates on the scrubland than on the agricultural land use, and they were more stable under moist than under dry conditions (Table 2). The differences found with the TDI test were smaller than with the other tests due to the low energy applied. It was evident that the aggregates of the arid site under scrubland use had a similar behaviour to that of the aggregates of the agricultural land use at the wettest site.

The test CND also showed that soils beneath scrubland were more stable than soils under agriculture land use. This was confirmed for arid, intermediate and wet climates (Table 3). Aggregate stability also decreased along the gradient in average values. For both, agricultural and scrubland cover, and under dry and moist conditions, the aggregates were more erodible on the

Table 1
Mean value and standard deviation (S.D.) of the MEWDT index for the three samples measured[a]

	Time (min)					
	5		120		1440	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Agriculture land						
Wet site	0.2	0.1	0.5	0.2	0.9	0.2
Intermediate site	0.4	0.1	1.0	0.2	1.8	0.1
Arid site	3.6	0.3	3.9	0.1	4.0	0.0
Scrubland						
Wet site	0.0	0.0	0.0	0.0	0.1	0.1
Intermediate site	0.3	0.2	0.7	0.4	1.0	0.6
Arid site	1.6	1.6	2.5	1.3	3.2	1.0

[a] 0, No dispersion; 1, dispersion of some particles; 2, aggregate partly dispersed; 3, very large dispersion; 4, total dispersion.

Table 2
Water-drop impact test expressed as the percentage of sample surviving as aggregates after TDIs distinguishing between previous moist and dry conditions for each sample[a]

	Sites (%)					
	Wet		Intermediate		Arid	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Agriculture land						
Dry	44.7	27.9	20.3	5.0	5.0	4.8
Moist (1 kPa)	45.7	27.9	24.1	18.3	5.0	4.8
Scrubland						
Dry	78.3	8.1	71.1	6.1	44.2	7.4
Moist (1 kPa)	85.6	4.2	73.7	9.9	42.3	6.8

[a] Mean value and standard deviation (S.D.) for the arid, intermediate and wet sites.

Table 3
Water-drop impact test (CND) based on average number of drop-impacts necessary to broke down an aggregate distinguishing between previous moist and dry conditions[a]

	Sites (%)					
	Wet		Intermediate		Arid	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Agriculture land						
Dry	46.5	24.4	25.7	11.8	10.9	7.0
Moist (1 kPa)	53.3	41.0	36.2	33.9	10.5	8.1
Scrubland						
Dry	66.2	39.1	60.2	6.9	32.0	15.2
Moist (1 kPa)	96.6	17.0	64.8	33.1	24.2	9.8

[a] Mean value and standard deviation (S.D.) for the arid, intermediate and wet sites.

arid sites. It was also found that the variability within the samples and amongst samples was larger as the wetness of the site increased for the agriculture land use. Under this test, also the arid site on scrubland (44% surviving aggregates) had a similar behaviour than the wettest one under agricultural land use (45% surviving aggregates).

3.3. UD test

The UD test confirmed the larger stability of aggregates from the scrubland and the reduction of the soil stability along the climatological gradient. Table 4 gives information in mean values and standard deviation of the number of aggregates surviving after the treatment at different radiation energy (from 30 to 115 W). The scrubland showed the larger aggregate surviving number (93–54% surviving aggregates). The agriculture land showed the lower aggregate surviving number (48–12%). For both land uses, aggregate stability was greater on the wet site, decreasing to the arid site.

Fig. 3 shows the stability curves measured under different ultrasonic radiation energy and they explain the effect of land use and climate on the soil erodibility. Agriculture soils had lower aggregate stability than semi-natural scrubland soils and aggregate stability was greater for wet than for arid climates on both land uses. Within the scrubland use the aggregate stability was much lower for the arid site, meanwhile the wet and the intermediate showed a similar behaviour: very large stability. On the agriculture land use a progressive decrease in aggregate stability was found from the wet to the arid site. A similar behaviour was observed between the arid site of the scrubland use and the wet site under agriculture land use.

Table 4
The UD test showing the total number of aggregates surviving at different energy applications (from 30 to 115 W) during 5 min[a]

	Sites (%)					
	Wet		Intermediate		Arid	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Agriculture land	44.7	11.7	30.3	6.5	11.7	4.0
Scrubland	102.7	21.2	93.0	5.2	53.7	13.3

[a] At each measurement 10 aggregates were used (190 aggregates in total). Mean value and standard deviation (S.D.) for the arid, intermediate and wet sites.

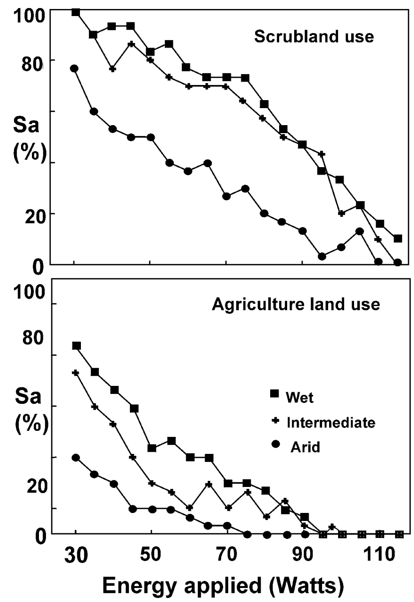

Fig. 3. UD test. Mean aggregate stability curve for the three sites selected along the climatological gradient under scrubland and agriculture land. Sa = percentage of surviving aggregates.

4. Discussion

The differences between agriculture and scrubland uses reflect the positive effect of vegetation on the development of stable soils and the effect of ploughing on the degradation of soil structure. The effects of cultivation on soil aggregation and aggregate stability have been studied by different authors and with different objectives (Low, 1972; Grieve, 1980; Chan and Heenan, 1996; Watts et al., 1996a,b). They show that tillage break up soil aggregates and due to the removal of the plants exposes aggregates to the raindrop impact and rapid wetting, which are the causes of the aggregate breakdown. It is also found that agriculture results in the physical disruption of the aggregates and favours less accessible organic matter to micro-organism and stimulates oxidation (Tisdall and Oades, 1982). Other authors found recently low aggregate stability under agriculture land use on semiarid environments (Ternan et al., 1996), together with a very fast crusting process already described (Farres, 1978).

On the other hand, vegetation cover favours much greater aggregate stability at the study case of scrubland. Vegetation favours a more advantageous climate for aggregate development due to the reduction of the maximum and minimum daily temperatures and the greater soil water storage (Cerdà, 1998a). Also vegetation results in the generation of organic bindings, roots and fungal hyphae which favours the development of aggregates (Oades, 1993; Cerdà, 1996; Degens et al., 1996). From the point of view of aggregate breakdown organic matter is important in reducing disruption arising from slaking pressures (Zhang, 1994), but may not be as effective in preventing aggregate breakdown by raindrop impact (Ternan et al., 1996). Nevertheless, the roots system favours the stability of soil structure (Oades, 1984). Although sometimes the relationships are not clear there is a broad consensus on the beneficial effect of organic matter on aggregate formation and stabilisation as Imeson and Verstraten (1985) found on highly calcareous soils in Spain. The influence of soil organic matter on aggregate stability in agriculture and semi-natural soils is also related to the dynamics of nematode communities (Ferris et al., 1996) and the microbiota and enzyme activity (García Alvarez and Ibañez, 1994), which improves the soil fertility.

On the research study area it was found a clear relationship between the soil organic matter content and the aggregate stability as it is shown in Fig. 4. There it is distinguished between the two land uses studied (agriculture and scrubland) and each of the three different climate conditions (wet, intermediate and dry). For both land uses there is positive relationship between soil organic matter and the resistance of aggregates to the breakdown. Soils covered by scrubs always have greater soil organic matter and more stable aggregates than do the bare agriculture soils. Differences between land uses at the same climate conditions are greater for the arid site and decrease until the wet site. On average values, soil organic matter is 3.36 times greater on the scrubland than on the agriculture land. This relationship is slightly different at each study zone. On the arid site, soil organic matter is 5.13 times greater, meanwhile this ratio is 3.78 and 2.58, respectively, for the intermediate and the wet site. Soil aggregate stability also has a similar behaviour: greater differences under arid conditions. In average values, aggregate stability is 2.23 times more stable under scrubland than on agriculture land, but this ratio moves from 2.91 on the arid site to 2.35 on the intermediate and 1.41 on the wet site.

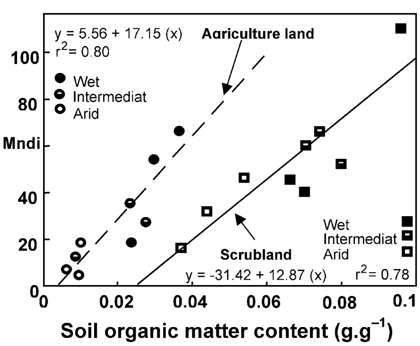

Fig. 4. Relationship between the soil organic matter content and the mean number of drop impacts (Mndi, CND test) necessary to reach the breakdown of 20 aggregates under dry conditions.

The above mentioned data suggest that, firstly, arid environments are more fragile to agriculture land use because cultivation results in a rapid degradation of the soil structure due to the exhaustion of the organic matter. Secondly, a reduction of the mean annual rainfall due to the expected climatic change will be more dangerous for agriculture than for forest or scrub covered areas due to the low aggregate resistance and the lower organic matter content. Climatic change at the tropical climatic zone will result in the general degradation of the soil structure if a reduction in the mean annual precipitation is produced. Different works have highlighted the effect of climate, and confirms that a reduction of soil aggregate is found with a decrease of rainfall. In two similar climatological gradients in Israel was found the same behaviour on semi-natural soils also affected by grazing (Lavee et al., 1991, 1996). Also in the Betic Mountains of Spain a decrease of aggregate stability from the wettest to the driest area was found (Cerdà et al., 1996). However, other authors found different trends along climatological gradients. Boix et al. (1995a,b) and Cerdà (1998b) found that the effect of human interference's in Crete and southeast Spain, such as forest fire and grazing, can degrade some locations of the transect, and determines lower aggregate stability at the wet sites. Other authors found that under natural conditions — Colombian Rainforest — soil erodibility changes along the altitudinal gradients due to changes in climate (Imeson and Vis, 1982).

5. Conclusion

The three methods and the four tests applied confirm that agriculture is a driving force to the degradation of the soil structure. The reduction of mean annual rainfall also leads to a degradation of the soil structure. These results reflect that the land use can exert similar or greater influences on the soil structure than a climate change. The combination of both, increase in aridity and agriculture, will lead to land degradation processes to be more active.

Acknowledgements

The project "farmer strategies and production systems in fragile environments in mountainous areas of Latin America" (EC Contract TS3*-CT91-0017) financed the fieldwork campaign. The laboratory tests were performed in the laboratory of the Department of Physical Geography and Soil Science at Amsterdam University. David Preston and Anton Imeson are acknowledged for the support in Tarija and Amsterdam. FEDER-CICYT IFD97-0551 project and the *Secretaría de Estado de Universidades*, *Investigación y Desarrollo* with a contract of the *Reincorporación de Doctores y Tecnólogos a grupos de investigación en España* also financed this research. The manuscript was improved by Prof. M.R. Carter and Prof. J.M. Tisdall, and the language reviewed by A.C. Thornes.

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